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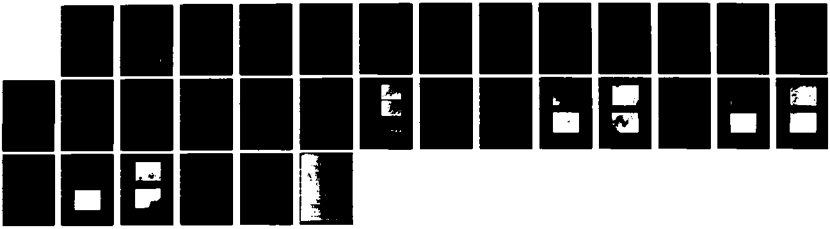

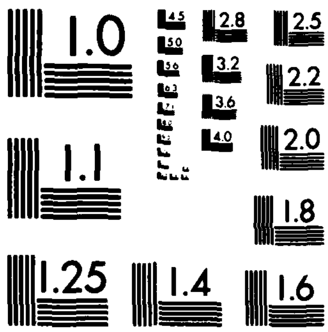

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PULSED LASER DEVICE DEVELOPMENT PROGRAM

MIRROR DEVELOPMENT FOR PULSED LASERS

M. J. Smith

AVCO EVERETT RESEARCH LABORATORY, INC.
a Subsidiary of Avco Corporation
2385 Revere Beach Parkway
Everett, Massachusetts 02149

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Surface diagnostic techniques were reviewed to determine if new or novel methods could help achieve an understanding of the laser mirror pulsed fluence failure problem. Dye penetrants were found ineffective, but ultrasonic baths appear to be useful to remove weakly attached surface regions. Acoustic and thermal wave microscopy appear relevant, but could not be experimentally evaluated in this work.

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Various coppers and copper alloy samples were procured and examined. A sputtered dispersion-hardened alloy of 1% SiC in copper was found to have superior uniformity in composition and hardness, and produced a polished surface superior to those previously obtained at Avco with OFHC copper.

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1.0 INTRODUCTION

This report describes fairly basic work aimed at understanding the metallurgical factors relevant to advanced design mirrors for pulsed infrared lasers. We have avoided here the question of multilayer dielectric mirrors, as this technology involves intricate proprietary processes and is more appropriately addressed by the various coating vendors. It should be kept in mind, though, that metal mirrors have for these applications outperformed dielectric ones, a situation that seems likely to continue, since the technology problems for dielectric mirrors are at least as difficult as those for metal.

In Section 2.0, we review the physical basis for various failure modes of metal mirrors. The present work is aimed at two of these mechanisms: first, the so-called thermal defect failures, which appear to be the immediate limiting factor for laser devices of present interest; and second, surface fatigue damage arising from repetitive thermal stresses.

In Section 3.0 we discuss possible nonlaser diagnostics for finding thermal defects. Section 4.0 deals with the surface properties of several candidate types of copper, and how these may or may not inhibit thermal defects and resist thermal stresses.

Since the present program was funded only to a degree sufficient to make a good start into the overall problem, we conclude in Section 5.0 with suggestions for further work.

2.0 REVIEW OF PULSED MIRROR FAILURE MECHANISMS

A. INTRODUCTION

A number of damage mechanisms which limit the operation of highenergy pulsed metal mirrors have been postulated from theory or have been observed. It is possible that new ones may be discovered as experience is gained in operating mirrors at high surface energy densities.

Figure 1 shows a map of the domains of the main performancelimiting mechanisms which have been identified for the important case of copper mirrors. Five mechanisms are shown: clean air breakdown, single-pulse surface melt, fatigue damage (single and multiple pulse), thermal defect failures, and surface contaminant (dusty mirror breakdown). These will be discussed below.

B. CLEAN AIR BREAKDOWN

Focused laser beam experiments have shown that clean air at standard conditions is ionized and suffers breakdown for intensities greater than about 4×10^9 W/cm^2. Allowing for reflection and coherent interference, a mirror will thus undergo surface breakdowns at about 1×10^9 W/cm^2. This defines a fundamental limit for atmospheric pressure lasers. This is in excess of any presently known requirement, hence it is not of concern here.

C. SINGLE-PULSE SURFACE MELTING

Small-spot mirror testing has shown that mirrors inevitably suffer plasma breakdown (if all other failures are avoided) at or near the limit set by surface melting in a single pulse. The absorption coefficient for metallic surfaces at 10 μm is well approximated by a linear variation with temperature.[1] If the absorption coefficient is given by

$$\alpha = \alpha_0 + \alpha_1 T \qquad (1)$$

then the fluence E_m to melt the surface can be obtained from

(1) Sparks, M. and Loh, E., JOSA 69, p. 847 (1979).

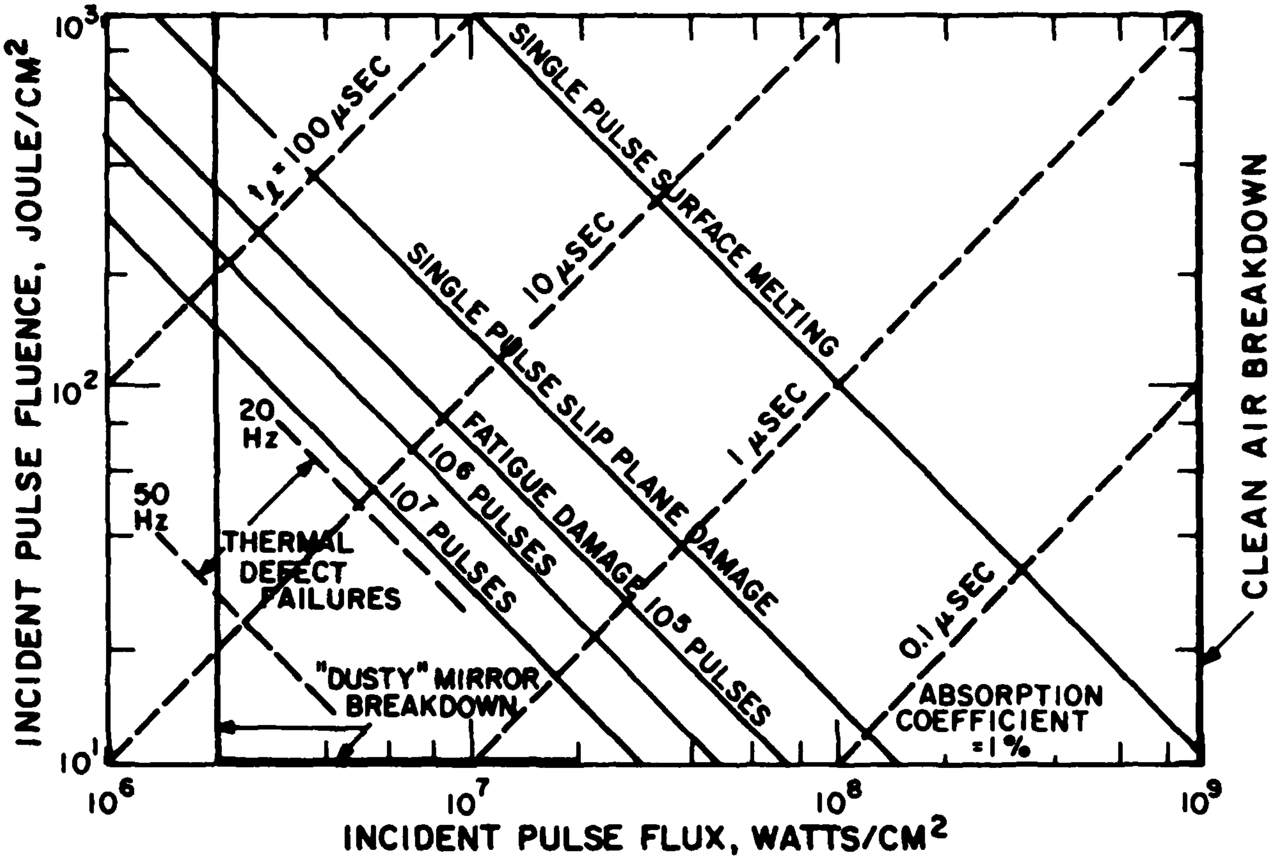

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Figure 1. Mechanisms Affecting Pulsed Laser Mirror Performance (Copper Mirror Case Shown)

$$T_m = \frac{\alpha_o}{\alpha_1}\left\{\frac{\left[\exp\left(\frac{\alpha_1^2\, E_m^2}{\kappa\ \rho\ C\ \tau}\right)\right]}{\left[1 + \left(1 - \exp\left\{- \frac{4}{\pi}\frac{\alpha_1^2\, E_m^2}{\kappa\ \rho\ C \tau}\right\}\right)^{1/2}\right]} - 1\right\} \tag{2}$$

where

T_m = temperature rise to melt surface ($\simeq$ melt temperature in degrees Celsius)

τ = pulse length

κ = thermal conductivity

ρ = density

C = capacity

It is necessary to use this equation rather than the more familiar one,[2]

$$T_m = \frac{2}{\sqrt{\pi}} \frac{\alpha_o\ E_m}{(\kappa\ \rho\ C\ \tau)^{1/2}} \tag{3}$$

which comes from assuming an absorption coefficient which is independent of temperature ($\alpha_1 = 0$), because almost all materials of interest for mirror construction exhibit considerable variation in absorptivity between room temperature and T_m. However, for $E \ll E_m$, Eq. (3) is satisfactory. It should be noted that surface melt is the same if the ratio $E_m/\sqrt{\tau}$ is kept constant. Figure 2 shows surface temperature rise for copper, as a function of fluence, for two values of τ_p. We have used a $\alpha = 0.01 + (0.01/300)T$ (°C). It will be seen that ~ 350 J/cm^2 is required for surface melt (~ 10^3°C) in 10 μs.

D. FATIGUE DAMAGE

At the end of a laser pulse, a thin layer of metal has been heated, but this heat has not diffused into the bulk of the mirror substrate. As a result, this layer suffers a compressive thermal stress, given by

(2) Carslaw, H.S. and Jaeger, J.C., Conduction of Heat in Solids, 2nd ed., Ch. II, Clarendon Press, Oxford (1969).

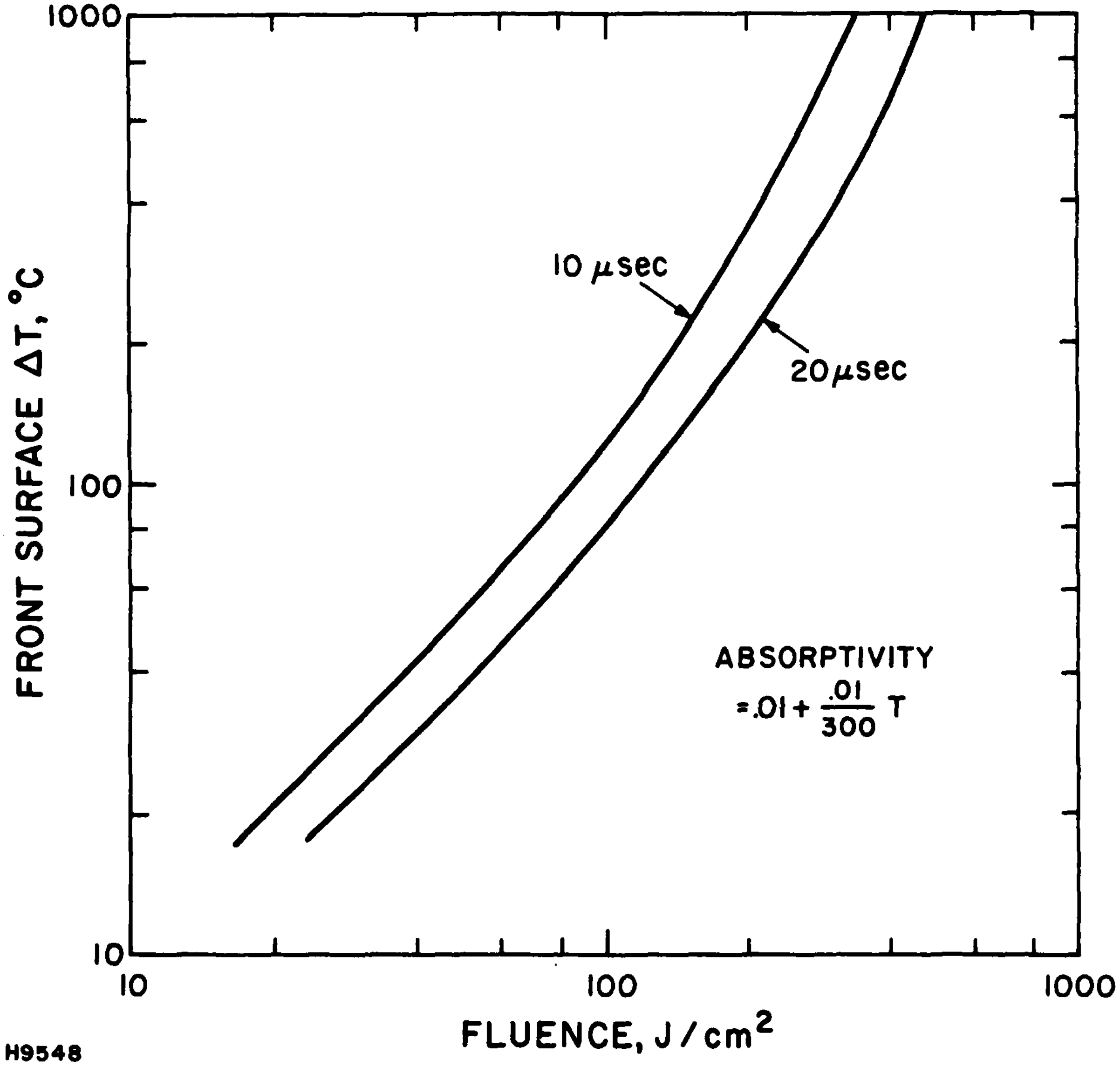

Figure 2. Copper Mirror Single Pulse ΔT

$$\sigma = \frac{\alpha Y \Delta T}{1-\nu} \quad (4)$$

where

ν = Poisson's ratio

α = coefficient of thermal expansion

ΔT = surface temperature rise at the end of the laser pulse [calculable from Eq. (3)]

Y = Young's modulus

When this stress exceeds the surface tensile yield stress σ_y, plastic deformation occurs. The yield stress for IR mirror materials (particularly copper) is a very strong function of the particulars of surface work hardening, impurities, and alloying. For very pure, annealed copper, the physical properties are:

yield stress	σ_y	~	3000 psi
	α	=	$1.7 \times 10^{-5}\ K^{-1}$
	Y	=	1.8×10^{7} psi
	ν	=	0.34

for which the critical ΔT [by Eq. (4)] is only 22°K, corresponding to about 20 J/cm^2 in 15 μs. However, mirrors are generally not constructed using annealed copper. The curve on Figure 1 shows results for typical "halfhard" OFHC copper, which suffers single pulse plastic deformation with 200 J/cm^2.

Neither calculations nor experiments to date have established a clear relationship between surface plastic yield and the onset of plasma detonations, so it is far from certain to what extent mirror performance is actually affected by small-scale plastic yield at the surface, at least on a single-pulse basis.

However, repetitive pulsing raises the possibility of accumulated fatigue damage, causing mirror failure. Cyclic mechanical stressing of metals is well known to cause fatigue failure. A correlation by AERL[3] of rotating beam fatigue test data for tough pitch copper (not quite as pure as OFHC) gives the alternating stress (in psi) for n stresses as

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(3) Sutton, G.W., "Stress and Dynamic Endurance of Metal Mirrors for Repetitively Pulsed Lasers," presented at the Twelfth Boulder Symposium on Optical Materials for High-Power Lasers, Boulder, CO, 30 September - 1 October 1980.

$$\sigma_n = 1.57 \times 10^5 \, n^{-0.127} \, (1 - 0.004 \, \Delta T)$$

The number of pulses needed to exceed the yield stress is also shown on Figure 1. The implicit assumption here is that the thermomechanical stress cycle is reasonably similar to that of the rotating beam tests.

As is evident from the figure, the apparent fatigue life limits for copper mirrors are low enough to be of concern. Again, though, we face the question of assessing mirror failure likelihood arising from this mechanism: the assumption of stress exceeding yield stress leading to mirror failure is just that - an unverified (though not unreasonable) assumption.

E. THERMAL DEFECT FAILURES

Mirror testing has generally been conducted on a single-pulse or few-pulse basis. However, recent test results at AERL using up to 50 pulse bursts, have indicated an apparently hitherto unreported failure mode. Mirrors which survive one or a few pulses are seen to fail after a number of pulses, when these pulses are delivered in a burst mode.(4) Failure likelihood increases for longer bursts and higher rep-rates.

These failures are consistent with (though do not conclusively prove) a thermal defect model, in which a portion of the surface is postulated to be in poor thermal contact with deeper portions of the substrate. The thermal contact is good enough to not overheat on a single-pulse basis, but eventually the whole portion is heated by average power absorption during repped operation so that the nth pulse pushes the local surface above the plasma initiation point.

F. SURFACE CONTAMINANT FAILURES

Lencioni(5) has shown (Figure 3) that dust in the air lowers the plasma initiation threshold considerably. The dusty mirror limit shown on Figure 1 presumes 20 μm dust; dust of this size is routinely present on optical components prepared and handled in typical room environments. Straightforward preparation and handling techniques have been shown to limit surface dust breakdown to the extent that it is not, in general, the limiting failure mode.

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(4) Smith, M.J. and Itzkan, I., "Repetitive Pulse Large Area Testing of Copper Mirrors with 10.6 μm Radiation," presented at the Topical Meeting on High-Power Laser Components," Boulder, CO, 2-3 October 1980.

(5) Lencioni, D.E., Appl. Phys. Lett. 23, p. 12 (1973).

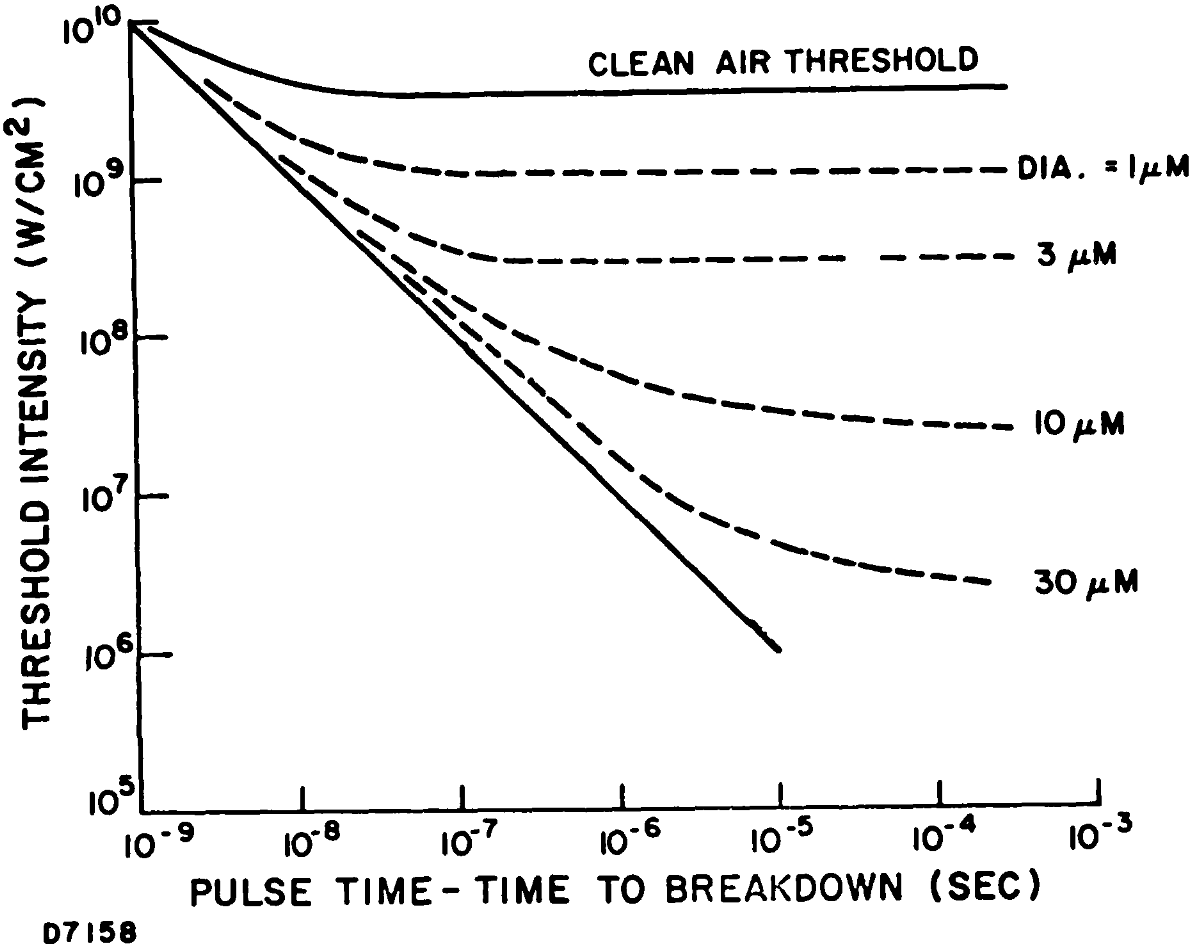


Figure 3. Dusty Air Breakdown

3.0. METAL MIRROR SURFACE DIAGNOSTICS

We can categorize imperfections likely to cause thermal defects as flakes, inclusions, or voids, as shown in Figure 4. Flakes arise naturally as part of the polishing process (see Figure 5), since there will always be parts of the surface where crystal grains are almost, but not completely, worn away. Inclusions can be impurities in the raw mirror stock, or foreign material (e.g., abrasive grit) impressed during polishing. Voids are gas bubbles that become trapped during the original material solidification. They are probably the least likely thermal defect, since metals are typically cold worked from ingot into plate or rod, and it is not obvious that a spherical bubble could survive in the final material.

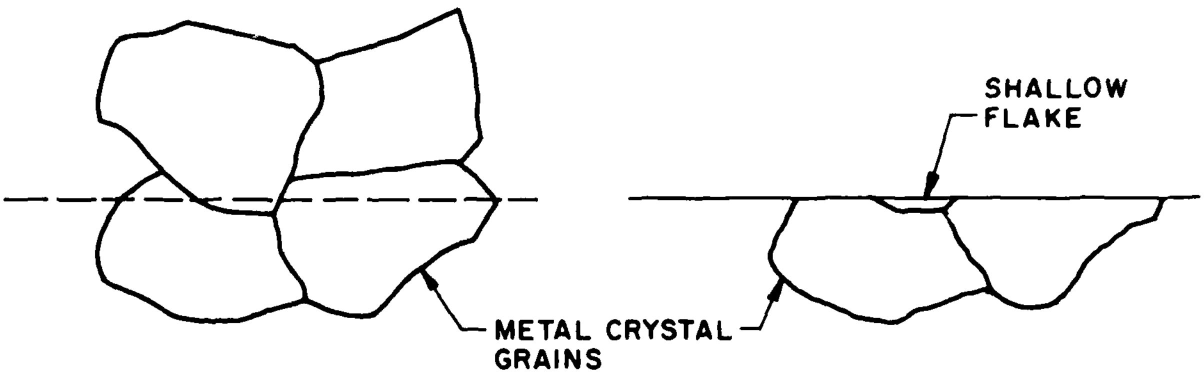
Identifying the presence of defects is difficult particularly if they are slightly subsurface and hence hidden from microscopic view, or else have been obscured by polishing. One task we undertook was to review surface-diagnostic technology; the use of such techniques could minimize the need for actual high-power laser irradiation of samples.

Table 1 summarizes the various types of diagnostics. Ion and e-beam probes are fairly routine tools for chemical analysis, though they do require fairly small samples in order to fit within specimen vacuum chambers. A scaled-up probe capable of examining entire HEL mirrors would clearly be an ambitious project in its own right.

A promising new technology involves the use of acoustic or thermalwave microscopy. These microscopes are essentially "radars," in the sense that they measure disruptions in the subsurface propagation of acoustic or thermal waves. They have already been applied to locating hidden flaws in integrated circuits, seam welds, and laminated capacitors, and apparently have the fine spatial resolution necessary to look for flaws relevant to metal laser mirrors. At this time acoustic microscopy on a commercial service basis is available from Sonoscan, Inc., Bensonville, Illinois, while thermal wave microscopy is provided by Therma-Wave Inc. of Fremont, California. We have had discussions with these companies; however, evaluation by them of mirror samples requires funding beyond what could be spared from the present program. Estimates for sample holder tooling, setup, and initial specimen evaluation are of the order of $5K. We would recommend that such work be included in future mirror development activity.

A common, commercially available surface diagnostic is fluorescent dye pentrant, often used for crack detection in automotive and aerospace applications. We procured a sample of "Tracer-Tech" brand penetrant from Uresco, Inc., of Cerritos, California. The material comes in spray cans, and consists of a fluorescent dye in a wetting agent vehicle. After spraying the penetrant on the sample, it is allowed to set for several minutes, and then gently washed

Figure 4. Flaws Capable of Generating Thermal Defects



(b)

Figure 5. Polishing Granular Material Inevitably Causes Shallow Flakes

TABLE 1. SURFACE DIAGNOSTICS APPLICABLE TO LASER MIRRORS

Diagnostic	Type	Destructive Test	Comments
E-beam/ion probe analysis (various type available commercially)	Chemical Species Identification	No	Small samples only. Hard to detect low-z atoms (e.g., carbon).
Metallurigical etch	Subsurface Crystal Structure	Yes	Removes immediate surface layer, so hidden flaws may be revealed.
Microscopy (visible or SEM)	Surface Structure	No	Interpretation sometimes ambiguous.
Microscopy (acoustic or thermal wave)	Subsurface Structure (particularly voids or density changes)	No	Small samples only. New, promising technology.
Fluorescent pentrant dyes	Surface Cracks or Porosities	No	Widely used technique, though not applied to mirrors before. Results apparently negative.
Ultrasonic cleaning bath	Surface weak regions	Presumably, only to flaw sites	Not a standard "diagnostic," but may help catalog surface homogeneity of various samples.

so as to remove all the dye except that which has seeped into cracks or holes. The test piece is then examined under a UV lamp for any telltale glows. We tried "Tracer-Tech" on several mirrors, with apparently negative results. After washing the surface dye off, we placed the specimens under an optical microscope, and side-illuminated with the UV lamp. Residual dye was observed as glowing blobs resting distinctly on the mirror surface, but none was observed in any of the usual pits or polishing scratches. Varying the degree of surface wash did not alter these observations. Evidently, then, mirror surface flaws of a porous nature either do not exist, or else are not receptive to these pentrants.

A thermal defect implies a weak mechanical connection between some surface feature and the underlying material. Results of previous repetitive-pulse laser testing suggest that thermomechanical strain may act to dislodge or alter these defect sites, leading to breakdown. Supplying an equivalent stress, without the use of a laser, clearly constitutes then a surface diagnostic, or perhaps a laser surface stress simulator. It has been recognized for some time that the forces generated by ultrasonic cleaning baths are sufficient to disrupt optical surfaces,(6) particularly after long exposures.

Figure 6 shows an example of Avco-specification OFHC copper that has been ultrasonically processed. The top micrograph shows a typical polished surface, with a few pits (more on these in Section 4.0) and the usual linear scratch marks from the polishing grit. The middle picture, after a five minute cleaning time exposure, shows the onset of surface damage, with the appearance of a number of extra pits and blemishes. After 15 minutes, as at the bottom, the entire region is pock-marked, and the mirror appears to the unaided eye as having a hazy appearance.

If we presume that the weaker surface areas are removed first, then a promising hypothesis is that such treatments may improve mirror resistance to burst-mode failures. Clearly, mirrors with varying periods of ultrasonic cleaning should be laser tested. It is not clear whether a surface as badly eroded as in Figure 6c is desirable optically, if for no other reason than to minimize diffuse scatter. However, it has been demonstrated by the University of Dayton Research Institute in work sponsored by the Air Force, that macroscopic dents do not affect mirror fluence limits, so that a poor-appearing (to the eye) mirror may in fact perform well in an IR laser system. A related question is whether ultrasonically cleaned mirrors can be repolished, and whether these mirrors will then likewise exhibit enhanced damage thresholds.

(6) Gibbs, W.E.K. and McLachlan, A.D., "Ultrasonic Cleaning of Optical Surfaces," in Laser Induced Damage in Optical Materials: 1975, NBS Special Publication 435 (April 1976).

a) BEFORE ULTRASONIC CLEANING

b) AFTER 5 MIN. ULTRASONIC CLEANING

c) AFTER 15 MIN. ULTRASONIC CLEANING

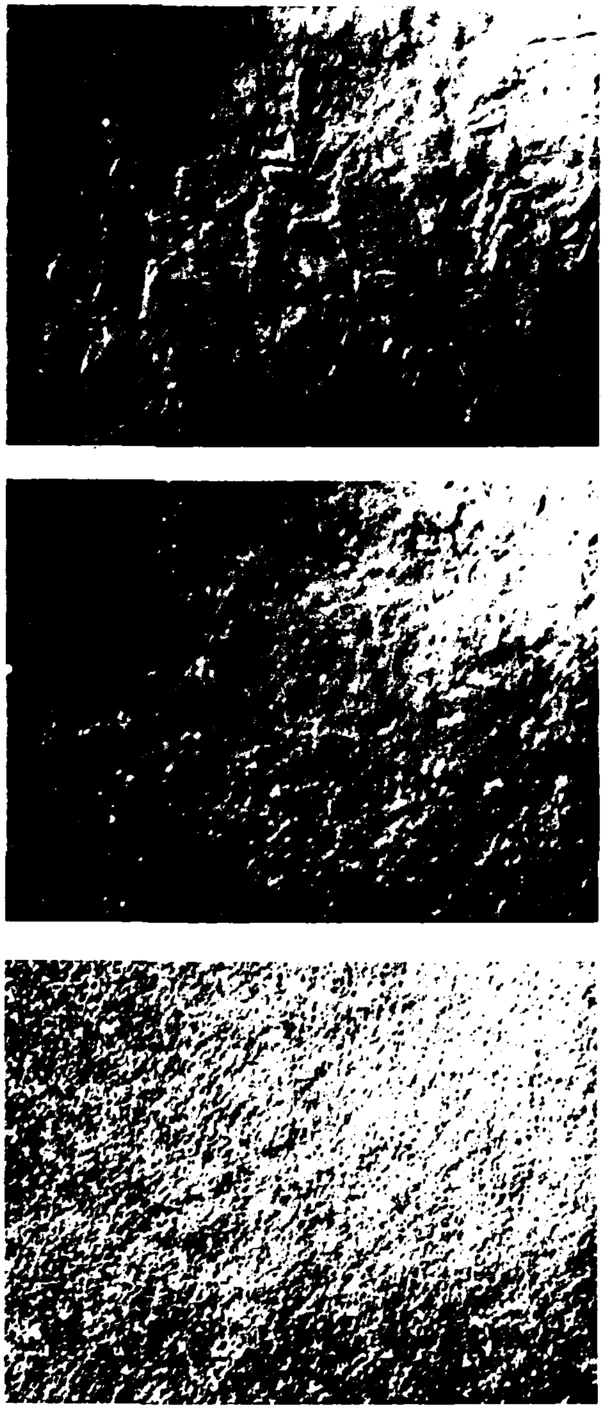


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Figure 6. Surface Erosion Caused by Ultrasonic Clearing

4.0 MIRROR METALLURGICAL INVESTIGATION

The major portion of the presently funded mirror development effort involved a review of the metallurgical properties relevant to mirror surfaces, and the procurement and examination of samples.

As is well known, the theory of the optical properties of metals indicates an intimate relationship between the infrared reflectivity of a smooth metal surface and its electrical conductivity. Thus, high reflectivity mirrors are generally fabricated from copper, molybdenum, tungsten, and similar materials. Since copper mirrors have in the past shown the highest singleshot damage thresholds, we have chosen here to limit our investigation to examining various forms and alloys of copper.

Metals and alloys are generally described in a macroscopic sense by their chemical composition and hardness, but it is clear that to understand the mirror fluence breakdown problem, a more microscopic view is necessary. It then is necessary to consider:

1. Chemical composition and uniformity on a microscale.

2. Crystal grain size and stability.

3. Local variations in hardness (which obviously affects polishing on the microscale). This combines the effects of 1 and 2.

Hardness is related to the other parameters in that it arises as a consequence of smaller and/or more stable crystal grains.

Based on this, we procured a variety of coppers and copper alloys which include a range of crystal grain sizes and stabilities:

1. Tempered commercial OFHC copper. This material is less pure than zone refined, but, more important, is hardened to a "halfhard" condition by mechanical working.

2. Dead soft high purity copper. This was obtained from Materials Research Corporation and is prepared by zone refining. Nominal purity is 99.999 percent, and the material is represented as being free from internal voids.

3. Three percent chromium copper. This much chromium is not soluble in copper, so that compositional variation is to be expected on the microscale. The chromium acts as a hardening agent in that it pins the crystal grain boundaries and limits their mobility.

4. "Amzirc" alloy, which is 0.15 percent zirconium. The zirconium is completely soluble in copper, and acts as a dispersion hardening agent, which disrupts the copper lattice structure.

5. Sputtered 1 percent SiC/99 percent Cu. We had a number of substrates coated in this fashion by Battelle Northwest Laboratories, using a proprietary sputtering technique. Silicon carbide is not soluble to 1 percent in copper, yet, because of the manner of its deposition, it is uniformly distributed throughout the copper. This "nonequilibrium alloy," as it is termed, has a very fine structure or may be amorphous in places.

Figure 7 shows a Nomarski photomicrograph of a freshly polished tempered OFHC copper mirror surface, typical of those produced at Avco. Several features deserve comment. The "geographic relief" seen on the low power micrograph is precisely that: slight hardness variations in the copper crystal grains are polished away differentially. Also visible are polishing scratch marks and a pit.

The evidence of past laser damage tests indicates that polishing scratches do not appear to contribute to fluence breakdown. Damage sites are not seen to be clustered along or centered on scratch lines, and the degree of "scratchiness" (related to the final size polishing grit used) does not seem to influence the breakdown threshold.

Of more concern are the pits, which are fairly evenly distributed across the surface. We have in the past seen at least a qualitative correlation between the number of these pits and the ease of fluence damage, and suspect that they are in fact thermal defect sites. The bottom micrography at 1000X, shows the fairly ragged structure at the bottom.

The formation mechanism for these pits is unclear. Our optical shop technician believed them to be bubbles or voids uncovered during the polishing process. An alternative is that they represent flakes (as in Figure 5) that have been scoured from the surface, or perhaps embedded polishing grit that has been pulled from the surface. This latter seems unlikely, as one would expect on occasion to see polishing grit that had <u>not</u> been pulled out -- which we have not. Our original view was to agree with the technician and blame voids in the material.

However, as Figure 8a shows, pits are present even in high purity material known (or at least guaranteed) to not have internal voids. It seems, then, that these pits most likely have to do with flakes that have been removed. An experiment to verify this would be to surface-remelt a sample (via e-beam, X-ray or focussed cw laser irradiation) and then repolish: the optical resolidification process would rearrange the grain boundaries so as to absorb all the odd bits of copper into large crystals.

The larger crystal grain size expected for an annealed material is also illustrated in Figure 8a; the wedge-shaped crystal grain at the rightside of the micrograph is uniformly recessed, slightly below the rest of the surface.

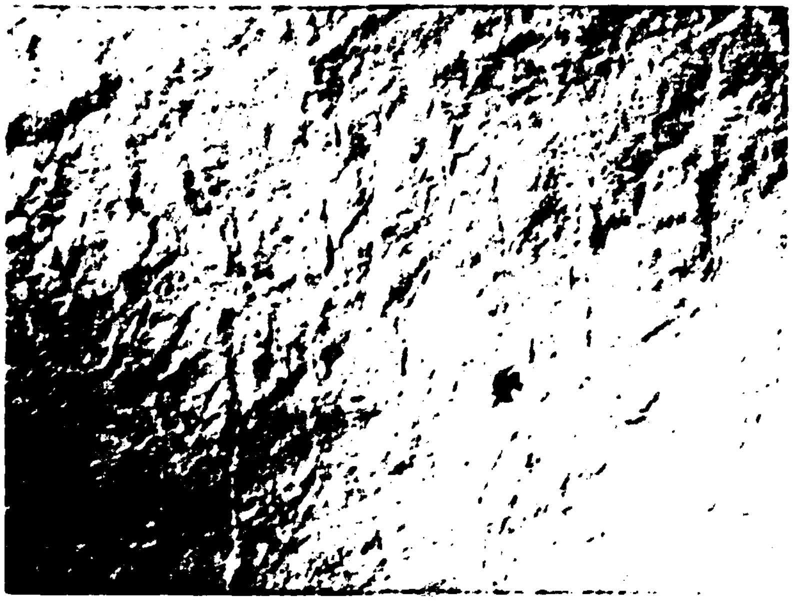

Figure 7a. Typical Tempered OFHC Copper Mirror. Magnification 50X.

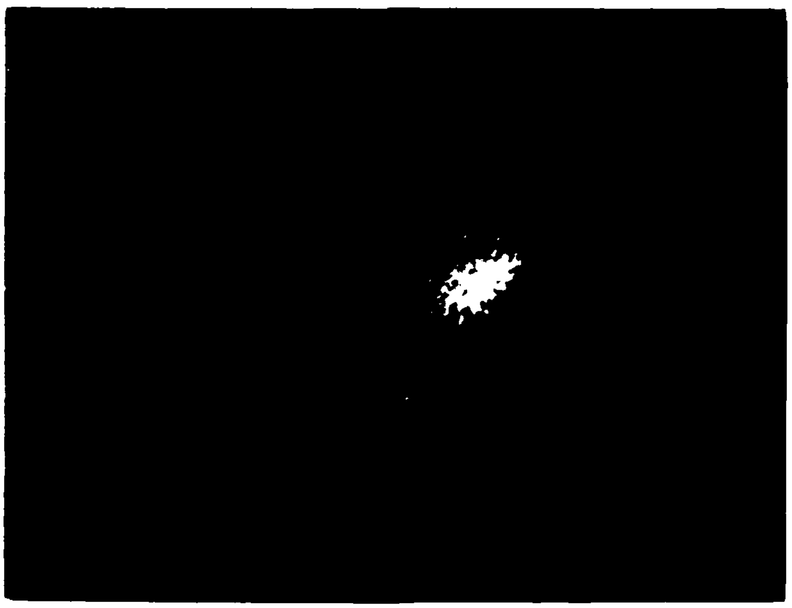

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Figure 7b. Enlargement of Surface Pit in a) Showing Structure. Magnification 1000X.

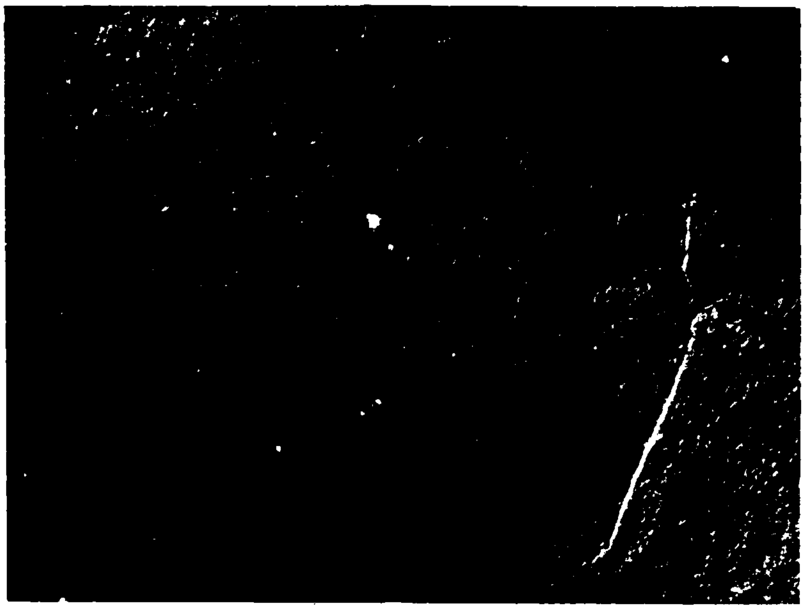

Figure 8a. Zone Refined Ultra-Pure Copper, Magnification 50X

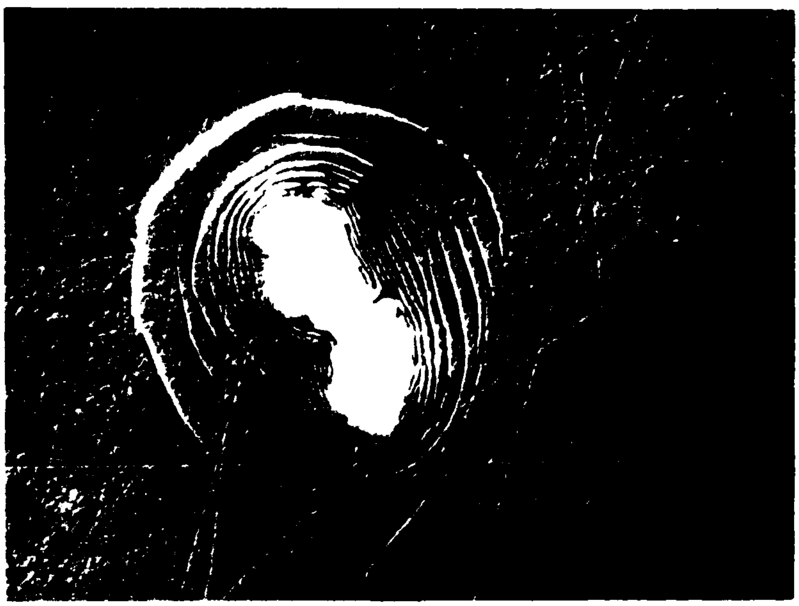

Figure 8b. Same Sample as a) Polishing Forces Acting on an Impressed Contaminant Particle have Generated Slip Lines. Magnification 400X.

Figure 8b shows stress slip lines which can be generated when applied forces exceed the yield stress (~ 10,000 psi). In this case a piece of contaminant (most likely room dust) has become embedded in the copper. The fact that such rings are not seen around any of the surface pits would seem to indicate that the pits could not have been the sites of embedded foreign particles.

Figures 9a and 9b show polished portions of a 3 percent chromium copper. This sample was supplied by Kennecott Copper Co. as representing one of the macroscopically harder alloys, of those which are nearly all copper. However (as in the case with most of the materials suppliers that were contacted), they were unsure of the surface microstructure that would result from mirror polishing.

Figure 9a shows several interesting features. First, the precipitation of the chromium at the grain boundaries is readily seen. Note, however, that the outlined crystal grains are much smaller than those of the first two materials. In addition, there seem to be none of the larger pits. Increasing the magnification to 1000X (Figure 9b) reveals the presence of very small pits, which appear to be the result of individual chromium particles forcibly extracted from the copper. Apparently as residual small bits of chromium are scoured from the holes, they create the radial scratch marks seen.

We have never tested this particular material as a high energy laser mirror, but it seems highly probable that the chromium particles would function as very active thermal defect sites, both because of the high IR absorption of chromium and because of the apparent ease with which they can be dislodged.

A better material would be one hardened in such a way that the hardening agent does not form discrete precipitates. We obtained a sample of "Amzirc" copper (0.15 percent zirconium), which is such a material. Its properties are similar to the more familiar beryllium copper, except for the toxicity factor. Low magnification photomicrographs (Figure 10a) show numerous pit defects, similar to those of the tempered OFHC material, except that there are more of them. This may be explained from the "flake" model for pit formation by simply observing that the crystal grains are much smaller and hence more numerous. The small crystal grain size also causes the differential polishing relief apparent with the chemically pure coppers, to be absent here. The enlargement of Figure 10b shows similar pit bottom detail compared to pure coppers. When viewed by the unaided eye, the numerous pits give a pronounced "orange peel" appearance to the sample. By comparison, orange peeling in OFHC copper mirrors is caused by the differential polishing relief seen in Figure 7.

If surface pits arise from leftover tips of nearly-removed crystals, then a way to avoid such flaws would be to prepare an amorphous material lacking any well-defined structure, or else a material whose crystal grain size is so small — much less than an IR wavelength — as to appear amorphous.

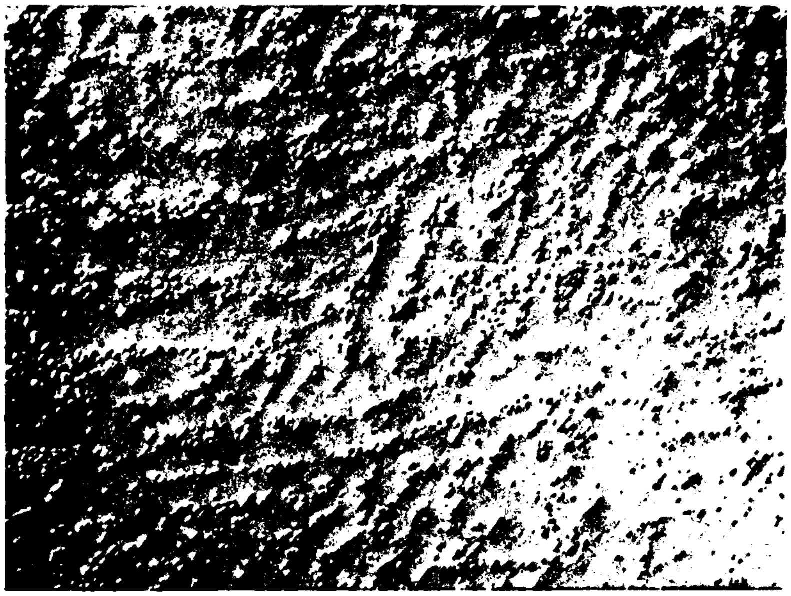

Figure 9a. 3 Percent Cromium Copper. The chromium has precipitated at the copper crystal grain boundaries. Magnification 200X.

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Figure 9b. Enlargement of a) Magnification 1000X. Polishing is seen to extract individual chromium particles, producing ragged craters.

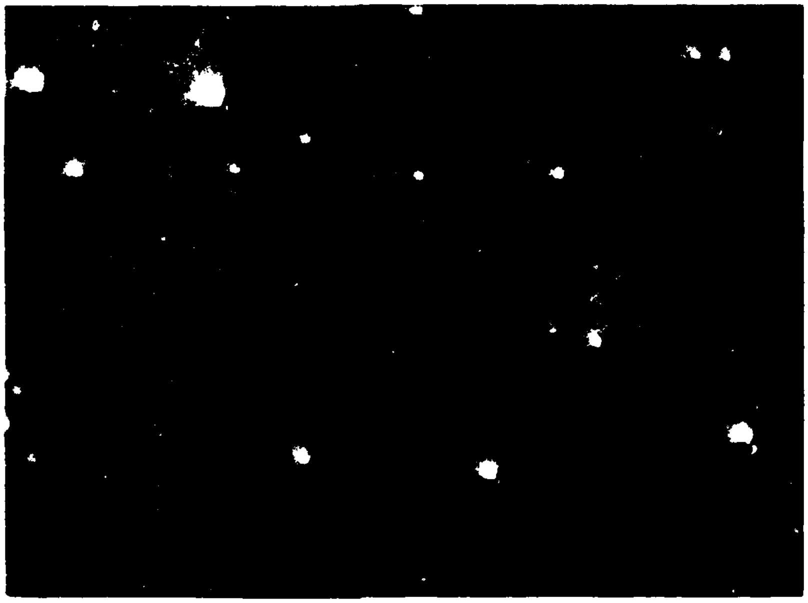

Figure 10a. "AMZIRC" Copper Alloy, Showing Numerous Pit Defects (50X)

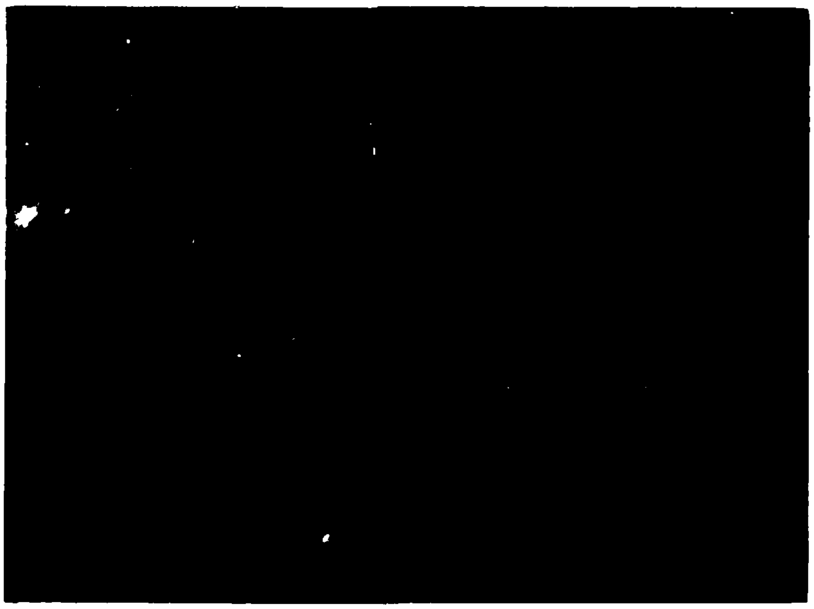

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Figure 10b. Same Specimen as a) Except Magnification 200X

Sputter coatings are known to have these properties, and so we procured some test samples sputter coated by Battelle Northwest Laboratories of Richland, Washington. They have been developing this technology for approximately ten years, originally in the context of nuclear metallurgy research, but more recently in connection with laser mirrors.

The sputter coatings consisted of 1 percent silicon carbide in 99 percent OFHC copper. If such a material were prepared by ordinary techniques, the SiC would collect at grain boundaries and look rather like the chromium copper discussed previously. However, the effect of the sputtering process is to spread the hardening agent uniformly in what is termed a nonequilibrium alloy. Such a material must not be brought near the copper melt temperature lest chemical segregation take place.

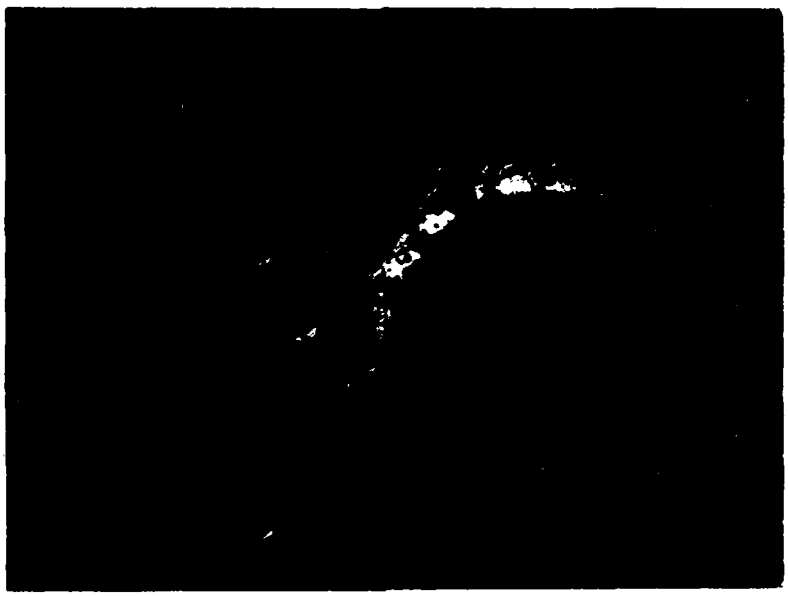
Figure 11 shows the "as received" surface of one of the sputtered samples. We were disappointed when we observed occasional potholes (roughly one every 2-4 cm^2) which were all too apparent to the eye, and which we feared penetrated the applied layer, ~ 0.020 in. thick. The Battelle representative claimed these holes did not completely extend to the substrate, but rather surrounded conically-shaped dendrites extending up from the substrate surface. It was further claimed that these features could be eliminated by a more rigorous pre-sputter surface cleaning, and in any event, most or all should polish out before reaching the substrate.

This was confirmed when we began polishing the samples. Figure 12a shows the remnant of a large flaw, part way through polishing. Comparison with the illumination of scratch marks shows it to be indeed convex. Further polishing, Figure 12b, completely removed the protuberance. The resulting surface was entirely free of pits, dimples, or geographic relief, and is the smoothest polished copper surface we have seen to date.

The drawback to the process is cost, as the sputtering must be accomplished in vacuum vessels, which would have to be quite sizeable to accommodate HEL system mirrors. It would clearly be desirable to be able to obtain this degree of surface quality in a bulk material.

Finally, since we have mechanically polished all our sample specimens, we must also consider what differences might be obtained by diamond turning. The evidence seems to indicate that the most numerous apparent defects - pits - are due to leftover corners of crystal grains. Diamond turning may or may not pull these corners out (this clearly should be investigated), but even if they remain as part of the surface, they would not be well attached, since they do not share crystal orientation with neighboring regions of the surface. Thus we believe it unlikely that diamond turning of a surface, per se, will render it more resistant to burst mode failures.

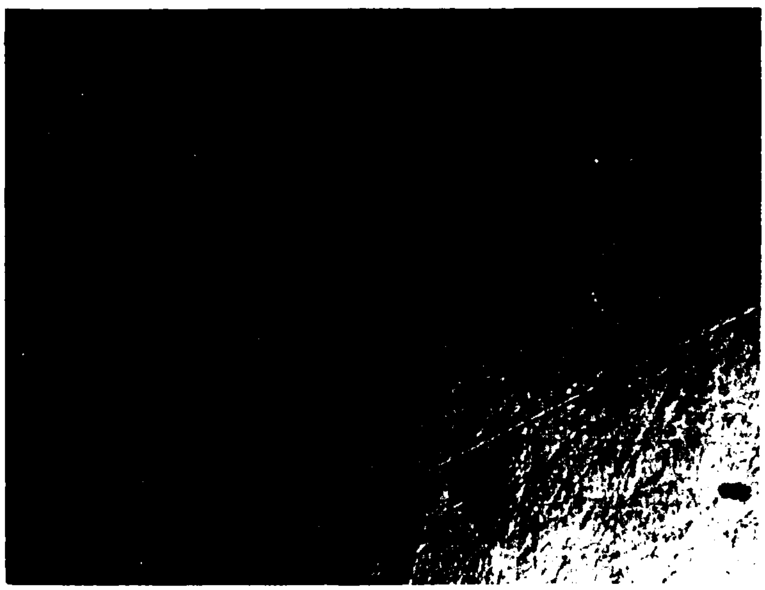
Figure 11a. Battelle Sputtered 1 Percent SiC/99 Percent Cu, Magnification 50X, Showing the "As Received" Material before Polishing. This area was free from large flaws.



K4565

Figure 11b. Same Sample as Above, also 50X, Showing Large Flaw Visible to the Unaided Eye

Figure 12a. Battelle Sputtered Sample Part Way through Polishing Sequence. Large flaw has been almost polished out. Magnification 50X.



K4564

Figure 12b. Same Sample as a) After Further Polishing. Magnification Now 200X. Note the complete absence of any structure except polishing marks.

5.0 RECOMMENDATIONS FOR FURTHER WORK

a. The effectiveness of acoustic or thermal-wave microscopy should be checked.

b. Ultrasonic bath processing of surfaces should be more comprehensively evaluated. Specific questions are:

   1. Does the treatment preferentially remove the weakest surface areas; i.e., does repolishing create a surface more resistant to ultrasonic bath stresses than before? And, of course, how do they survive multiple pulse mirror testing?

   2. What happens to the sputter coated surface? Would it delaminate?

c. Surface remelt techniques should be tried, with large temperature/time gradients, to further reduce crystal grain size, particularly in material such as the Amzirc copper.

d. Metallurgical investigation must be coupled to further laser testing, to evaluate the ideas and hypotheses developed here.

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